

Evaluation and Comparative Analysis of Radio-Wave Propagation Model Predictions and Measurements

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Abstract: This paper describes recent analyses performed on propagation model predictions and comparisons of those predictions with measured data. The specific radio-wave propagation prediction model is the Irregular Terrain Model (ITM) developed by the Institute for Telecommunication Sciences. The model is valid at frequencies from 20 to 20,000 MHz. Descriptions of specific problems encountered with analyses and comparisons of predicted versus measured data are discussed. The major results of this study are:

1. Model predictions are extremely sensitive to the magnitude of the effective antenna height, and an alternative effective antenna height algorithm is necessary to improve prediction accuracy.
2. A terrain database that does not accurately represent the propagation path will severely impact the model loss predictions.
3. When the measured data samples are correlated, (i.e., not independent), a multivariate statistical analysis of the available measured data must be used to properly assess stochastic behavior.

Keywords: radio-wave propagation, terrain database, effective antenna height

1. Introduction

Recent analyses comparing propagation model predictions with measured data were performed to gain insight to improve radio-wave propagation model prediction accuracy. The specific radio-wave propagation prediction model analyzed was the Irregular Terrain Model (ITM). ITM was developed by the Institute for Telecommunication Sciences for the prediction of radio-wave propagation loss on tropospheric circuits at frequencies from 20 to 20,000 MHz [1]. The available measurement database is an extensive amount of measured data collected in the 1960's and early 1970's over a variety of terrain types (plains, hills, and rugged mountains) at frequencies from 20 to 10,000 MHz. Three very important considerations encountered with analyses and comparisons of predicted versus measured data are discussed which include: different implementations of the effective antenna heights, the accuracy of terrain databases, and the statistical analysis of the data. These three considerations were addressed in detail. The first two have the most profound effect on propagation model prediction errors. The third involves the proper statistical treatment to use to determine how well modifications or improvements to the model perform against the measured data.

It was found that different implementations of effective antenna height can change predicted propagation loss values by as much as 45 dB. In some situations the effective antenna height can be comparable to the structural antenna height and in others it can be vastly different. The results of this study will be used to improve the effective antenna height algorithms contained in ITM. During the study of terrain databases, it was found that in some cases the various different terrain databases had widely varying terrain heights for the same geographic location. It was necessary to consult topographic maps to ascertain the correct terrain elevations for these locations. The actual terrain has a very significant impact on propagation model prediction accuracy. The measured data available for comparison with the model predictions were found to have a high degree of correlation amongst individual data samples. In particular, the data along each propagation path was found to be highly correlated with other data taken at other antenna heights and frequencies on the same path. Multivariate statistical analysis techniques must be used to correctly analyze this correlated data and provide a metric to properly assess the stochastic behavior of the difference between predicted and measured propagation loss values.

2. The ITM Propagation Model

The ITM propagation model computes long-term median transmission loss for tropospheric circuits over irregular terrain. This method is applicable for frequencies between 20 and 20,000 MHz. In the point-to-point mode the model uses terrain data over the great circle path between the terminals to make predictions of median values of attenuation relative to the transmission loss in free space, known as the reference attenuation. For the line-of-sight (LOS) scenario, the calculated reference attenuation is based on a two-ray model, which includes an extrapolated amount of diffraction attenuation. The reference attenuation for a transhorizon scenario is the smaller of either the diffraction attenuation or forward scatter (i.e., troposcatter) attenuation. The diffraction attenuation is a convex combination of smooth-Earth diffraction and double knife-edge diffraction. The distance from each terminal to its radio horizon is preserved in the knife-edge computations. The troposcatter attenuation computation is an empirical algorithm described in [2]. Values of reference attenuation in each scenario are continuous functions of distance, and are matched at the smooth-Earth horizon distance. The smooth-Earth horizon distance is computed using the effective Earth's curvature and the effective antenna heights. Among other influences, this accounts for the sensitivity of the model's predictions to the effective antenna heights.

The minimum input data that the ITM model needs for computation in the point-to-point mode include: the terrain profile, the radio frequency in MHz, the path distance in km, and the structural antenna heights above ground in meters. Additional input parameter values for climate, surface refractivity and ground constants can also be selected by the user. The structural antenna heights and the terrain elevation profile are used to calculate: the terrain roughness parameter, the effective antenna heights, the horizon distances, and the horizon elevation angles.

3. Effective Antenna Height Algorithm

ITM uses effective antenna heights throughout most of the computer program instead of structural antenna heights. ITM uses the structural antenna heights only when computing horizon elevation angles, distances to horizons, and Fresnel zone clearances. This use of different effective antenna heights has a significant impact propagation loss predictions. Thus, the correct value of reference attenuation depends heavily on these values of effective antenna height. Effective antenna height was observed to change the predicted propagation loss by as much as 45 dB relative to predictions using only a structural antenna height.

Transmitter and receiver effective antenna heights above the dominant reflecting plane are computed by the algorithm within ITM described below. The effective antenna heights along the propagation path are determined from the terrain contour, the structural antenna heights above ground level, and the distances to the horizon from each of the antennas.

For the LOS scenario, a “least squares” fit to the terrain profile along the propagation path over the region of interest measured from the transmitter and receiver antenna locations is extrapolated to determine the “least squares” terrain elevation values at each end of the path. The calculations are performed in a region of interest that begins and ends at the minimum of either fifteen times the transmitter or receiver structural antenna height, or one-tenth the distance to the horizon from the transmitter antenna or the receiver antenna, respectively. The effective antenna height at each end of the path (transmitter and receiver) is then determined by adding to the structural antenna height at each end, respectively, the ground level at each antenna minus the appropriate “least squares” terrain elevation value if the “least squares” terrain elevation value is less than the ground level at that antenna. If the “least squares” terrain elevation value is greater than the ground level at that antenna, then nothing is added to the structural antenna height.

For the transhorizon scenario, the effective antenna heights are determined by performing two “least squares” fits to the terrain in regions of interest near the transmitter and receiver antennas. One “least squares” fit for the transmitter region of interest begins at the minimum distance of either fifteen structural antenna heights or one-tenth of the distance to the horizon from the transmitter antenna, and ends at a point on the path at nine-tenths of the distance to the horizon from the transmitter antenna. The transmitter effective antenna height computation uses the value of the “least squares” fit to the terrain extrapolated to the transmitter antenna location. The other “least squares” fit is calculated for the receiver region of interest which begins at the minimum distance of either fifteen receiver structural antenna heights or one-tenth the distance to the horizon and ends at a point on the path at nine-tenths of the distance to the horizon measured from the receiver antenna. The receiver effective antenna height computation uses the value of the “least squares” fit to the terrain extrapolated to the receiver antenna location. The effective antenna height at each end (transmitter and receiver) is then determined by adding to the structural antenna height at each end, respectively, the ground level at each antenna minus the appropriate “least squares” terrain elevation value if the “least squares” terrain elevation value is less than the ground level at that antenna. If the “least squares” terrain elevation value is greater than the ground level at that antenna, then nothing is added to the structural antenna height. This is done in a similar manner as was done for computing effective antenna heights for the LOS scenario. The difference is that the region of interest for the transhorizon scenario is confined to being near the transmitter and the receiver antennas, whereas for the LOS scenario most of the region of interest between the transmitter and receiver antennas is used.

4. Effective Antenna Height Study

The ITM program was used to examine propagation paths found in the measured data. Two antenna height cases were used to examine the effective antenna height behavior. First, the existing ITM effective antenna height algorithm was used to select the effective antenna height. For the second case, the effective antenna height was fixed at the structural antenna height. Propagation loss predictions were made for most of the propagation paths in the measured database. The predicted value of propagation loss was compared with the measured value of propagation loss for both antenna height cases. The loss deviation is the predicted value of attenuation from the model minus the measured value of attenuation. If the deviation

is negative, then it implies that the predicted loss is less than the measured loss. If the deviation is positive, then it implies that the predicted loss is greater than the measured loss.

The comparison of ITM predictions to measured data has generated a number of different behavior characteristics related to the internal computation of effective antenna height that are being investigated. This investigation will provide guidance in selecting an improved effective antenna height computation. There are cases where ITM computes a large effective antenna height that differs substantially from the structural antenna height. This results in a large deviation between the value of median transmission loss predicted and the measured value of transmission loss. There are cases where, if the effective antenna height were made equal to the structural antenna height, then the deviation can be reduced, but there are just as many cases where a large deviation occurs. That is, for situations with the effective antenna height equal to the structural antenna height, many cases exist where the deviation resulting from measured paths using the effective antenna height is much smaller than the deviation for the measured paths using the structural antenna height.

There are also many measured paths where the optimum value of effective antenna height is somewhere between the ITM determined effective antenna height and the actual structural antenna height. The effective antenna height is always greater than or equal to the structural antenna height. Further study of the behavior of ITM in different scenarios will provide information for the development of a new effective antenna height algorithm that minimizes the deviation between predicted and measured propagation loss.

5. Terrain Database Issues

Two considerations in the use of a terrain database are: the database to select for profile extraction (3 arc-sec USGS, 3 arc-sec DTED Level-1, or manually extracted data from 1:24,000 topographic profile maps), and what extraction interval to use. All terrain databases are not equivalent: some provide data that differ significantly for the same geographic location. It was found that the original USGS terrain database was quite deficient in providing correct values for terrain height when compared to values from topographic maps or the values from DTED Level-1 data. It was found that for paths in Northeast Ohio, the USGS showed mostly flat terrain, where the other two terrain references indicated terrain profiles with 100-meter elevation variation. Even though the DTED Level-1 terrain database is closest to the manually extracted terrain data, that database has sometimes yielded terrain elevation data that differs appreciably from the manually extracted data. Most of the analysis work performed to date has subsequently relied on the DTED Level-1 terrain database, but a recently issued USGS terrain database (1 arc-sec) has shown very significant improvement over the older USGS terrain database. This improvement was significant enough to warrant its use in future propagation model studies. This new USGS terrain database has just been released and will be used in future studies.

There are tradeoffs in the selection of the terrain extraction interval to use for obtaining terrain elevations from any one of these sources. A short terrain extraction interval requires larger databases and produces longer propagation model prediction run times, but results in greater resolution of terrain for increased prediction accuracy. A longer extraction interval provides less terrain resolution and would produce errors in describing terrain, when intermediate terrain elevation values were determined by linear interpolation. The larger extraction interval would provide shorter computation times, but could miss some significant terrain variation detail that could possibly change a LOS path to a diffraction path. The true variability

of the terrain might not be accurately represented with the long extraction interval. It was found that some propagation loss prediction models work better with a particular extraction interval. Extraction intervals of 100, 200, and 450 meters were investigated. The ITM model works best with the 200-meter extraction interval.

6. Multivariate Statistical Analysis of Correlated Data

ITM is an empirical model in the sense that its “deterministic” results are modified by extensive comparisons to measured data to account for parameters that the model does not control. The set of measured data consists of over a dozen different measurement data sets containing more than 41,000 measurements, which span the frequency range from approximately 20 to 10,000 MHz. The data was taken over paths in different states of the continental United States, such that many different types of terrain (plains, hills, mountains, etc.) were included. A wide variety of antenna heights and polarizations for the transmitter and receiver antennas were used to perform the measurements at many frequencies.

If the available data used to develop the empirical model can cover all possible propagation situations, then the model should apply as a general tool to perform radio-wave propagation predictions along any path. However this is an ideal situation, and it is most likely that propagation situations exist for which the model would make poor predictions. Extensive as the available data for ITM is, there are still propagation scenarios that are not contained in this database. Also the data sets appear to have substantial correlation present between data within individual datasets. This does not mean that the data are unusable, because they can be used for propagation analysis, height-gain studies, and to assess frequency dependence.

This data correlation is a result of the fact that the measurements in many cases were made at multiple frequencies and multiple antenna heights on the same path. When propagation conditions for the measurements and hence predictions were found to be good or bad for a particular path, then they were good or bad for all frequencies and antenna heights along the path. Univariate statistical analysis of the data, where means, medians, and standard deviations are computed, relies on data samples in which the individual measurements have been randomly drawn from a very large universe or collection of radio-wave propagation measurements. These samples should be independent (uncorrelated) and have identical frequency distribution (independent and identically distributed). When the data samples are correlated, this independence assumption is violated.

A valid univariate statistical analysis might be performed if all of the data were taken on different measurement paths, but this is not the case. It is necessary to find ways to get rid of the correlation in the measured data. As our model of this correlation, the measurements on one path can be considered to be independent of measurements taken on another path. The excess loss relative to free space predicted by ITM was compared to the measured data, and the difference (predicted loss minus measured loss) was used as the statistical random variable. By segregating the data so that it is taken from different paths and constructing the covariance matrix, the analysis can proceed. The calculation and analysis of the eigenvalues and eigenvectors of the covariance matrix, which are also called the principal components, are guaranteed to be independent. This now enables the testing of the significance of the distribution of the means, medians, and standard deviations of the difference between model loss predictions and measured data. The eigenvalues of the covariance matrix are well ordered and all positive. For highly correlated data, some eigenvalues can be large and some can be close to zero. This results in highly heterogeneous samples.

7. Conclusions

When performing a comparison of radio-wave propagation predictions with measurements, one must be careful of certain pitfalls that can occur in such an analysis. Use of a reliable terrain database is required to get reasonable agreement of radio-wave propagation model predictions with measured data. The terrain extraction increment is also important. Effective antenna height is a difficult parameter to predict for both LOS and diffraction mode radio-wave propagation. Accuracy of model predictions depends very heavily on the transmitter and receiver effective antenna heights used in the model. ITM calculates an effective antenna height from the structural antenna height and the terrain profile between the terminals. Work in progress for the ITM radio-wave propagation prediction model includes the improvement of this effective antenna height computation to attain better agreement of predictions with measurements. If a statistical analysis of the data is to be performed, the data should be independent and identically distributed for a correct univariate analysis, otherwise the techniques of multivariate statistical analysis must be applied for correlated data to remove the correlation. This method of analysis will be used as a metric for determining the statistics of how well the improvements to the ITM model are working when compared to the measured database.

References

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